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Abstract of Thesis

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Title	Study on Structure and Sensorless Control of Brushless DC Motor for Hybrid Electric Vehicles (HEV車用ブラシレスDCモータの構造とセンサレス制御に関する研究)

Abstract of Thesis

In many industries, Brushless DC (BLDC) motor is actively used since it has many advantages such as low noise, high efficiency and long life span. Especially, a rapid growth of the Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) industries have increased the needs for high performance BLDC motor structures, which output high torque, consume low current and maintain stable operating state with decreased size and manufacturing cost at the same time, since many operating systems of them are comprised of electrical physical actuator systems which include BLDC motor. In addition, the needs for effective sensorless BLDC motor control algorithms, which can maintain the stability of the control characteristics in any environment, also increased in the EV and HEV industries since many electrical physical actuator systems of them are controlled without position detecting devices of BLDC motor. Because of this reason, study on novel structure and effective sensorless control of BLDC motor are actively conducted in many laboratories and companies.

In this research, first, a novel asymmetrical half-type Interior Permanent Magnet (IPM) BLDC motor is proposed for applying to Electric Oil Pump (EOP) of HEV. This IPM BLDC motor structure utilizes half-type Permanent Magnet (PM) configuration, only half the number of PMs is used than that of the conventional IPM BLDC motor, with all the magnets magnetized in the same direction. Also, the proposed asymmetrical half-type IPM BLDC motor has asymmetrical side gaps (slot next to the PMs) by widening side gaps, which locate at the parts those do not having magnets, and removing the thin bridges, which separate side gaps of the parts those having magnets and those do not having magnets, for reducing the torque ripples and leakage flux. Although the proposed asymmetrical half-type IPM BLDC motor uses 24 % less volume of PMs than that of the conventional IPM BLDC motor, neighboring magnets magnetized in opposite directions of each other, it is possible to create almost the same characteristics with that of the conventional IPM BLDC motor without increasing the motor size since the decreased leakage flux of the proposed asymmetrical half-type IPM BLDC motor makes it possible to make almost the same torque constant with that of the conventional IPM BLDC motor.

For verifying the usefulness and suitability of the proposed asymmetrical half-type IPM BLDC motor for EOP of HEV, the proposed asymmetrical half-type IPM BLDC motor is compared with the conventional IPM BLDC motor and three other half-type IPM BLDC motors, which have different side gaps, under various torque load conditions through Finite Elements Method (FEM) analysis. Then, experimental evaluation on the prototypes of the proposed asymmetrical half-type IPM BLDC motor and the conventional IPM BLDC motor is implemented under various torque load conditions. Finally, experimental evaluation on the EOP of HEV, which is assembled by the prototype of the proposed asymmetrical half-type IPM BLDC motor, is implemented at 85 °C oil chamber under various operating conditions. Through this research, it was possible to obtain the high performance IPM BLDC motor by the proposed asymmetrical half-type IPM BLDC motor, and also possible to verify the usefulness and suitability of the proposed asymmetrical half-type IPM BLDC motor for EOP of HEV.

This research also analyzes the effects of two types of back Electromotive Force (EMF) detecting electrical circuits on sensorless BLDC motor control for applying to sensorless controlled actuator systems of HEV. The 1st back EMF detecting electrical circuit, which uses a dynamic threshold level, always creates rotor position signals of almost the same average duty at various rotation speeds under no torque load condition since the dynamic threshold level changes automatically according to the maximum back EMF level. On the other hand, the 2nd back EMF detecting electrical circuit, which uses a static threshold level, always creates a different rotor position

signals duty at various rotation speeds under no torque load condition, and causes the sensorless BLDC motor control error frequently since the static threshold level is manually adjusted at the start of motor control, and it does not change according to the maximum back EMF level.

For verifying the usefulness and suitability of the 1st back EMF detecting electrical circuit, which uses a dynamic threshold level, for sensorless controlled actuator systems of HEV, electrical circuit simulation is implemented using general trapezoidal waveforms by changing the trapezoid peak. However, it is not possible to apply almost the same back EMF signals of BLDC motor and various rotation speeds under no torque load condition through electrical circuit simulation, and this makes it impossible to estimate the actual effects of two types of back EMF detecting electrical circuits on sensorless BLDC motor control. Because of this reason, coupled analysis of the FEM BLDC motor model and back EMF detecting electrical circuit is implemented at various rotation speeds under no torque load condition to estimate the actual effects of two type of back EMF detecting electrical circuits on sensorless BLDC motor control. It is the main target of this analysis. Especially, coupled analysis is implemented by applying both of full-type, neighboring magnets magnetized in opposite directions of each other, and half-type FEM BLDC motor models for obtaining more reliable analysis results. Finally, experimental evaluation is implemented at various rotation speeds under no torque load condition using a full-type 8 pole 12 slot IPM BLDC motor and embedded 3 phase BLDC motor controller. Through this research, it was possible to obtain more reliable analysis results since coupled analysis was implemented, and also possible to verify the usefulness and suitability of the 1st back EMF detecting electrical circuit for sensorless controlled actuator systems of HEV.

In addition, in this research, a half-type IPM BLDC motor is designed and analyzed for applying to sensorless controller integrated assistant EOP of passenger car. For verifying the usefulness and suitability of the designed half-type IPM BLDC motor for sensorless controller integrated assistant EOP of passenger car, coupled analysis of the designed half-type FEM BLDC motor model and the mathematically composed model of 3 phase BLDC motor controller, which creates the 3rd harmonics overlap of the sinusoidal waveform drive signal type, is implemented under various torque load conditions. Then, experimental evaluation on the prototype, which is assembled by the designed half-type IPM BLDC motor and sensorless controller, is implemented under various torque load conditions using an inverter without connecting the sensorless controller. Finally, the reasons for a difference between the results of coupled analysis and experimental evaluation are analyzed in detail.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

近年、低騒音、高効率で長寿命であるため、幅広い産業界でブラシレス DC モータ（BLDC）が主要な電気システムに使われるようになってきた。特に、電気自動車（EV）やハイブリッド車（HEV）へのニーズが急速に伸びており、モータの高トルク、低消費電力、製造コストなどへの要求が高まっている。このような状況において、様々な BLDC やそのセンサレス制御に関する研究が研究機関においてなされている。本論文では新しい BLDC の構造とセンサレス制御の提案を行い，解析及び試作機による実験検証により、その有効性を確認している。

第１章では、HEV 用 BLDC とその制御についての研究背景と研究計画について明らかにしている。

第２章では、HEV 用オイルポンプ（EOP）への適用をターゲットとして、回転子に有極と無極の磁極を交互に配置したハーフタイプの IPM 型 BLDC モータを提案し、その構造と動作原理を示している。更に、有限要素法（FEM）解析によりトルク特性、N-T（スピード−トルク）特性、損失及び効率などのモータ特性を求め、従来モデルとの比較により提案モータの有効性を明らかにしている。

第３章では、提案した BLDC の試作機による実験検証を行っている。コギングトルクの他、相電流、N-T 特性、効率など様々な負荷条件下での動作特性を測定し、従来機との比較評価により、提案モデルの優位性を示している。また、有限要素解析結果との比較により、解析の有用性についても確認している。

第４章では、電磁誘導検知型（back-EMF）センサレス制御手法を提案している。本手法はダイナミックスレッシュホールドの閾値を利用して、ロータ位置信号を常に出力する方法であり、HEV 用モータ制御に適用している。有限要素法との回路シミュレーション連成解析を用いて、本制御手法の有効性を確認している。

第５章では、提案した制御法の試作機による実験検証を行っている。様々な回転速度条件にて評価を行い、センサレス制御に有効であることを確認している。

第６、７章では、製品化レベルの HEV 用センサレスコントローラ内蔵の補助 EOP への搭載へ向けて、提案した BLDC モータをベースに応用設計している。有限要素解析及び実機による性能評価を行っており、その有効性を改めて確認している。

第８章では、本研究で得られた成果をまとめている。

以上のように、本論文は、HEV 用 BLDC モータとその制御に関する知見を明らかにしており、様々な産業分野への応用も期待できる。よって本論文は博士論文として価値あるものと認める。